LA-UR -91-2058

LA-UR--91-2058

DE91 014600

TITLE A NEW MODEL OF RATE DEPENDENT ELASTIC-PLASTIC FLOW

AUTHOR(S) James E. Hammerberg, Dean L. Preston and Duane C. Wallace

SUBMITTED TO APS 1991 Topical Conference on Shock Compression of Condensed Matter, Williamsburg, VA, USA

A NEW MODEL OF RATE DEPENDENT ELASTIC-PLASTIC FLOW

James E. HAMMERBERG, Dean L. PRESTON and Duane C. WALLACE

Applied Theoretical Physics Division
Los Alamos National Laboratory, Los Alamos, New Mexico

We present the results of 2D lagrangian hydrodynamic simulations of cylinder impact experiments using a recently developed model for rate-dependent elastic-plastic flow. This model, which takes advantage of empirical scaling relations in terms of melting temperature and shear modulus is consistent with the very high strain-rate behavior deduced from overdriven shock data and is in good agreement with the temperature and density dependence of the flow stress where known. Calculations for uranium and copper are discussed.

1. INTRODUCTION

The flow properties of real solids depend in a complicated way on the thermodynamic and defective state of the material. The evolution of the material ground state under conditions of large strains and high rates, however, is a formidable and unsolved problem of condensed matter physics. Models for the flow stress of solids which are based on single mechanisms for defect dynamics tend therefore to be of limited use outside a restricted range of pressure, temperature, strain and strain rate. The model which is discussed in this paper attempts to avoid some of these difficulties by using in an essential way the properties of materials in the strong-shock limit and the relevant lower-rate experimental data where available. It therefore makes possible reasonable interpolations between large strain, low rate behavior and high rate, low strain shock data. A second property of this model is that it takes into account the actual temperature and density dependence of the flow stress by using a scaled variable formulation, taking into account the most accurate calculational data available for shear moduli and melting temperatures. The following sections give a brief description of the model and comparisons with cylinder impact data which access the large-strain intermediate-rate constitutive behavior of copper and uranium.

2. A SCALED MATERIALS MODEL

The model we consider here is a complete model for the thermoplastic flow of solids. It represents the constitutive behavior of a material as a function of the mass density ρ, temperature T, plastic strain ψ, and plastic strain rate $\dot{\psi}$. The flow stress τ is taken to be a function of these variables $\tau = \tau(\rho, T; \psi, \dot{\psi})$. It is convenient to express stresses and temperatures in terms of scaled (dimensionless) quantities with stresses scaled by the isotropic shear modulus $G(\rho, T)$ and temperatures scaled by the melting temperature $T_m(\rho)$. The rate dependent quantities may also be scaled by a natural measure of frequency for shear motion, $\dot{\zeta}$, defined by

$$\dot{\zeta} = \frac{1}{2}\left(\frac{G}{\rho}\right)^{\frac{1}{2}}\left(\frac{4}{3}\pi\rho/M\right)^{\frac{1}{3}} \qquad (1)$$

which is approximately the inverse of the time for a shear wave to traverse a unit cell. Here M is the atomic mass. When scaled in this way the constitutive properties of materials exhibit striking regularities.[1]

The scaled variables are defined as $\hat{\tau} = \tau/G$, $|\hat{\dot{\psi}}| = \dot{\psi}/\dot{\zeta}$, and in terms of these quantities the particular form of our model is a modified Voce form.[2]

$$\hat{\tau} = \hat{\tau}_s - (\hat{\tau}_s - \hat{\tau}_y)\exp\left[-(N\psi)^{p}\right] \quad (2)$$

The exponential term takes into account work hardening. The scaled quantities $\hat{\tau}_s$ and $\hat{\tau}_y$ are rate dependent saturation and yield stresses defined in the following way:

$$\hat{\tau}_Y = max[Y_1, \hat{\tau}_{vhs}], \qquad (3)$$

$$\hat{\tau}_S = max[Y_2, \hat{\tau}_{vhs}]. \qquad (4)$$

Y_1 and Y_2 are the yield stress and the low strain rate saturation flow stress scaled by the shear modulus. $\hat{\tau}_{vhs}$ is the scaled flow stress at very high strain rates ($\geq 10^7$ sec^{-1}). We have determined this quantity by an analysis of overdriven shocks by Wallace[3] and from pressure shear data.[4,5] The very high strain rate limiting behavior is very well represented by a power law

$$\hat{\tau}_{vhs} = \alpha|\psi|^{\beta}. \qquad (5)$$

The saturation flow stress is temperature dependent and a good representation of the data is given by

$$A \ Y_2 = (a + b\hat{T})^{-1} \qquad (6)$$

A is a constant which takes crystal structure into account and a and b are constants as are α and β above. $\hat{T}$ is the scaled temperature defined above.

3. APPLICATION OF THE MODEL TO TAYLOR IMPACT EXPERIMENTS FOR COPPER AND URANIUM.

We have implemented the above model in a two-dimensional lagrangian continuum hydrodynamics code which is finite difference and uses a force gradient algorithm for calculating the time evolution of the field quantities. Typical mesh sizes were (20 x 60) in the r and z coordinates where the cylinder is symmetric about the z axis. The anvil cylinder interaction was simulated with a reflective boundary condition. Several zoning studies were performed and at this degree of resolution the simulations were essentially converged.

The parameters for ^{238}U were determined from Instron testing machine data,[6] Hopkinson bar data,[7] and the results of an analysis of overdriven shock data.[8] The parameters for OFHC copper are taken from the analysis of Preston, *et al.*[1] The values are given in Table I. The very high strain-rate data correspond to values of ψ of the order 10^9 - 10^{12} for both copper and uranium. The experimental data for uranium impacts are taken from the experiments of Gust.[9] The OFHC experiments we refer to are from Johnson and Cook[10]. The thermodynamic properties of the materials are taken from the LANL SESAME tables of thermodynamic properties.[11] The shear moduli and melting temperatures used in the scaled materials model are also taken from the new auxiliary SESAME tables[12] The results of these simulations and comparison with experiment are given in Table II.

Table I: Model Parameters for Uranium and Copper

Parameter	Uranium	Copper
Y_1	0.0020	0.00021
A	1.0	1.0
N	7.8	6.0
P	1.17	0.8
γ	0.56	0.20
α	64.0	141.0
β	0.305	0.202
a	64.0	141.0
b	220.0	387.0

Table II. Comparison With Experiment

Uranium:

T(°K)	$V_0 (m/s)$	$\frac{L}{L_0}$ (calc)	$\frac{L}{L_0}$ (expt.)
295	159	0.795	0.830
	138	0.829	0.856
	106	0.879	0.899
	180	0.755	
720	105	0.833	0.810
725	159	0 705	0.662
	139	0.756	0.727

Copper:

$V_0 (m/s)$	$\frac{L}{L_0}$ (calc)	$\frac{L}{L_0}$ (expt.)	$\frac{R}{R_0}$ (calc)	$\frac{R}{R_0}$ (expt.)
130	0.787	0.770	1.38	1.30
146	0.754	0.736	1.50	1.40
190	0.658	0.638	1.91	1.77

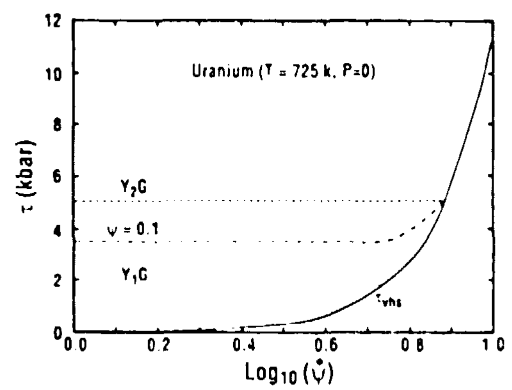

FIGURE 1

Flow stress vs. plastic strain rate.

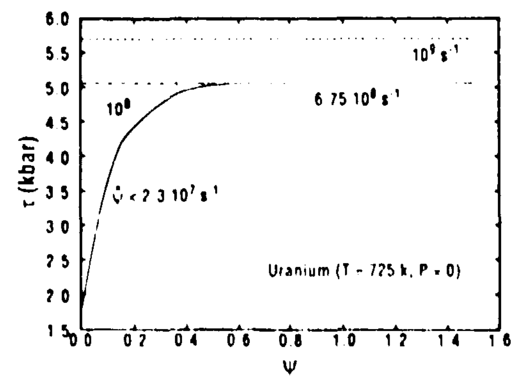

FIGURE 2

Flow stress vs. plastic strain.

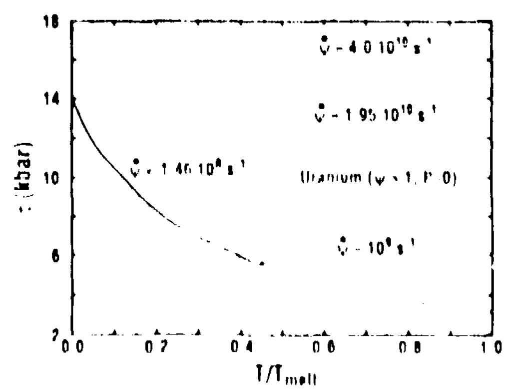

FIGURE 3.

Flow stress vs. temperature.

4. DISCUSSION

Figures 1 - 3 give an indication of the rate, plastic strain, and temperature dependence of the flow stress for uranium at 725°K. In the cylinder impact experiments the high-rate behavior occurs within the first 10 μsec, typically, and is fairly localized near the anvil-cylinder interface where temperature rises of a few hundred °C occur. Plastic strains of order unity are typical. Therefore in the Taylor impact experiment the initial deformation tests the higher rate properties of a given model and late time evolution is determined by large strain and temperature dependence of the flow stress. This is an intermediate regime for the present model for most of the evolution of the impact experiment. We find that the agreement with experiment is within a few percent for the final rod shape for the cases studied. We have not made an attempt to use the impact data to "improve" the parameters of the model since the microstructure of the materials is not well enough known. We have also not attempted to modify the anvil cylinder interaction by changing to a stick-slip interaction which is also not well enough characterized. We consider the level of agreement to be good considering that we have fit the rate-dependent data at very high strain rates and are in an interpolative regime as far as our model is concerned. We expect that in higher strain-rate regimes our model will become more accurate in predicting material flow. The overall agreement with the impact data is as good or better than that obtained with other standard models and indicates that we are treating the density and temperature dependence and work hardening well. Since our model is scaled with the most accurate values for shear moduli and melting temperatures presently available, we also have confidence that the temperature and density dependence of the flow stress will be limited to a large extent by our abilities to calculate these quantities. This, we believe, is a major strength of a scaled materials model for predicting material flow behavior in regimes of temperature, density and flow rate where experimental data may be very difficult to obtain.

l.

REFERENCES

1. D. L. Preston, D. L. Tonks, and D. C. Wallace, The Rate Dependence of the Saturation Flow Stress of Copper and 1100 Al, this conference.
2. J. E. Hockett and O. D. Sherby, J. Mech. Phys. Solids, 23 (1975), 87.
3. D. C. Wallace, Phys. Rev. B24 (1981) 5597; Phys. Rev. B24 (1981) 5607.
4. S. Huang and R. J. Clifton, "Dynamic Plastic Response of OFHC Copper at High Shear Strain Rates," Brown University, preprint.
5. Chin-Ho Li, "A Pressure-Shear Experiment for Studying the Dynamic Plastic Response of Metals at Shear Strain Rates of 10^5 s^{-1}," Ph D. thesis, Brown University (1982).
6. J. E. Hockett, P. S. Gilman and O. D. Sherby, J. Nucl. Mat. 64 (1977) 231.
7. P. E. Armstrong, LANL, private communication.
8. R. G. McQueen, S. P. Marsh, J. W. Taylor, J. M. Fritz, and W. J. Carter, in High-Velocity Impact Phenomena, edited by R. Kinslow (Academic, New York, 1970).
9. W. H. Gust, J. Appl. Phys 53 (1982), 3566.
10. G. R. Johnson and W. H. Cook, in Proceedings of the Seventh International Symposium on Ballistics, the Hague, The Netherlands, 1983, p 541.
11. K. S. Holian, ed. "T-4 Handbook of Material Data Bases," LA-10160-MS, (1984).
12. W. Slattery, J. D. Johnson, G. Straub, and S. Lyons, to be published.